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## On-Shore Central Hydraulic Power Generation for Wind and Tidal Energy

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### **Abstract**

Tidal energy, offshore wind energy, and onshore wind energy can be converted to electricity at a central ground location by means of converting their respective energies into high-pressure hydraulic flows that are transmitted to a system of generators by high-pressure pipelines. The high-pressure flows are then efficiently converted to electricity by a central power plant, and the low-pressure outlet flow is returned. The Department of Energy (DOE) is presently supporting a project led by Sunlight Photonics to demonstrate a 15 kW tidal hydraulic power generation system in the laboratory and possibly later submerged in the ocean. All gears and submerged electronics are completely eliminated.

A second portion of this DOE project involves sizing and costing a 15 MW tidal energy system for a commercial tidal energy plant. For this task, Atlantis Resources Corporation's 18-m diameter demonstrated tidal blades are rated to operate in a nominal 2.6 m/sec tidal flow to produce approximately one MW per set of tidal blades. Fifteen units would be submerged in a deep tidal area, such as in Maine's Western Passage. All would be connected to a high-pressure (20 MPa, 2900 psi) line that is 35 cm ID. The high-pressure HEPG fluid flow is transported 500-m to on-shore hydraulic generators. HEPG is an environmentally-friendly, biodegradable, water-miscible fluid. Hydraulic adaptations to ORPC's cross-flow turbines are also discussed.

For 15 MW of wind energy that is onshore or offshore, a gearless, high efficiency, radial piston pump can replace each set of top-mounted gear-generators. The fluid is then pumped to a central, easily serviceable generator location. Total hydraulic/electrical efficiency is 0.81 at full rated wind or tidal velocities and *increases* to 0.86 at 1/3 rated velocities.

## **1. Introduction/Background**

There are numerous ways to obtain non-carbon emitting, renewable electrical power. One of the objectives of this paper is to briefly review some of the state-of-the-art for wind energy and tidal energy systems. A new hydraulic energy transfer design will be discussed that allows centralized, ground-based power generation for on shore and off shore wind energy, as well as for tidal and river current energy.

### **1.1 Tidal Energy**

There are many different types of tidal power technologies. A partial list of categories includes the following (Reference 1).

**Barrage or dam:** A barrage or dam is typically used to convert tidal energy into electricity by forcing the water through turbines, activating a generator. Gates and turbines are installed along the dam. When the tides produce adequate difference in the level of water on opposite sides of the dam, the gates are opened. The water then flows through the turbines. The turbines turn an electric generator to produce electricity. Small power plants using this technology are now functioning in France, Russia, and Canada. The dams have been criticized, however, for resulting in silt and accumulation behind the dams.

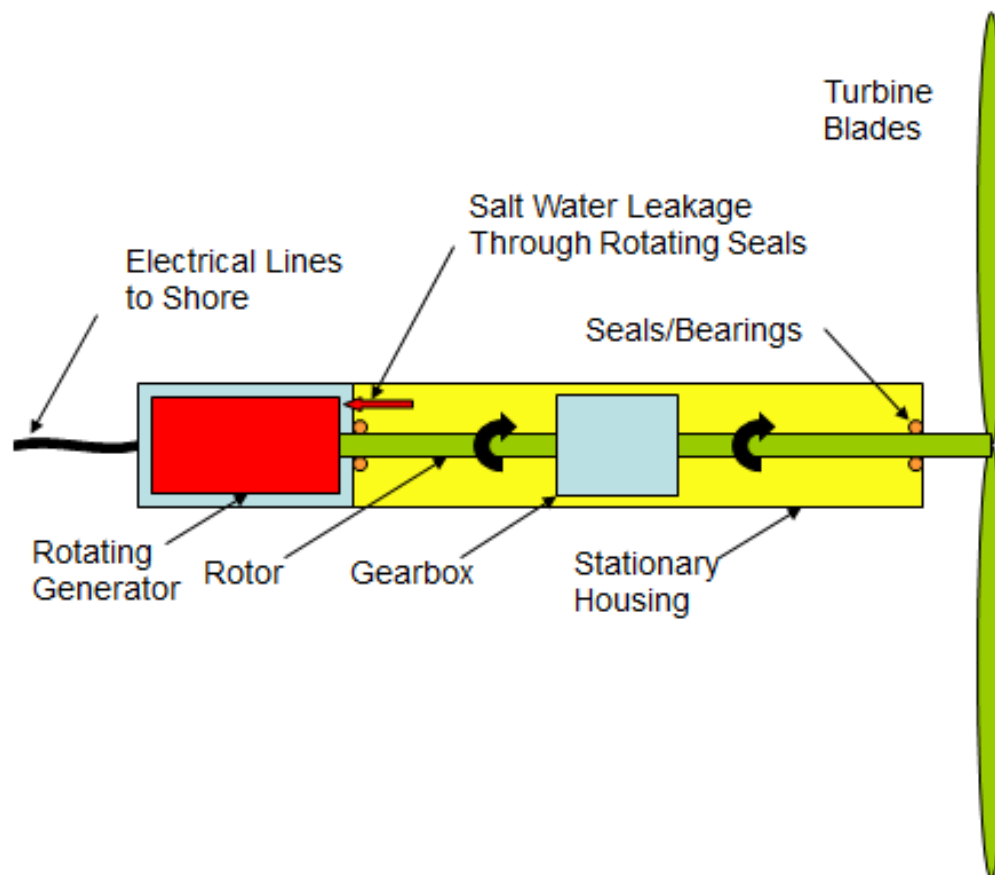
**Tidal Fence:** Tidal fences look like giant turnstiles. They can reach across channels between small islands or across straits between the mainland and island. The turnstiles spin via tidal currents typical of coastal waters. Some of these currents are 5-8 knots and generate as much energy as winds of much larger velocity. Tidal fences also impede boat traffic, as well as sea life migration.

**Horizontal Axis Tidal Turbines:** There are many types of horizontal axis tidal turbines. The most common of these tidal turbines look like wind turbines. They are arrayed underwater in rows, as in some wind farms. The turbines function best where coastal current run at between 3.6 and 4.9 knots, in currents of that speed, a 15-m diameter tidal turbine can generate as much energy as a 60-m diameter wind turbine. Ideal locations for tidal turbine farms are close to shore in water depths of 20-30m. This type of tidal turbine generally does not impede sea life migration or result in silt buildup.

The first tidal generator actually attached to a commercial grid in the United States was operated by Verdant Power in New York City's East River. Verdant's Roosevelt Island Tidal Energy (RITE) Project was initiated in 2002 and was operating on-grid intermittently until 2009. The project consisted of six, 35-kW horizontal axis turbines that were fully bidirectional and accumulated over 7000 hours of operation. A simple operational schematic of a horizontal blade tidal turbine system is shown in Figure 1. The tidal flow turns a blade at about 15 rpm, which is increased to about 1500 rpm by means of a gearbox. The higher rpm is then used to generate electricity by means of a submerged generator, and the energy is sent to shore with submerged power lines. The

project was plagued by a number of problems, including blades breaking off and salt water leakage into the generators. Reinforced turbines were installed in September 2008 (Reference 2), but they all eventually failed due to salt-water leakage into the submerged generators.

Atlantis Resources Corp, which is a partner in this DOE-sponsored task, has an 18-m diameter tri-blade system (Figure 2) which is named the AR-1000. It is a powerful and efficient single rotor turbine expressly designed for offshore ocean use. The AR-1000 combines a fixed pitch blade operation, a single stage gearbox, and a flexible coupling to the highly efficient permanent magnet generator with a rating of 1.0MW at 2.65m/s. In all the complete tidal turbine system is fully UK grid compliant employing features developed over the past 10 years.



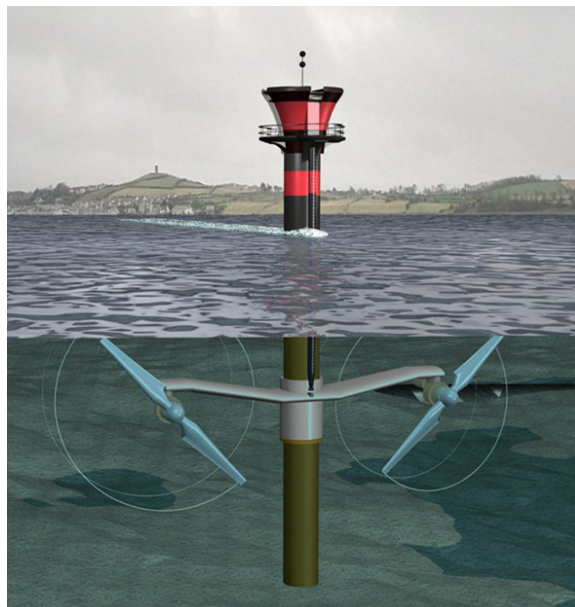
**Figure 1. Typical Horizontal Axis Submerged Tidal Turbine**



**Figure 2. Atlantis Resource 18-m Tidal Turbine**

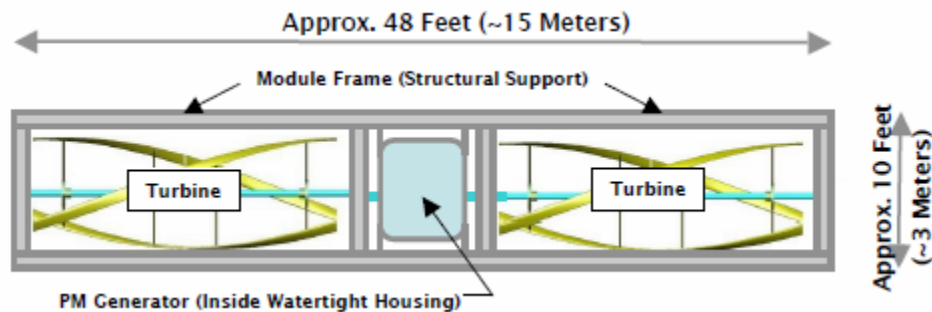
The AR-1000 was first connected and generated to grid in June 2011. This was achieved at the EMEC test facility using the same existing gravity based structure and connection platform developed for the revision generation AK-1000 turbine deployed in 2010. The testing of the device so far has proved that the water to wire efficiency of the device is in excess of 42% as predicted by the theoretical modeling. Testing of the system is still ongoing to refine the control system and to improve the overall system reliability.

There are numerous versions of horizontal axis turbines, including Marine Current Turbines, which use counter-rotating blades on a common tower (Figure 3) This design became the World's first operational in stream tidal turbine in 2008, when it generated 1.2 MW on Strangford Lough in Northern Ireland.



**Figure 3. Marine Current Turbine Arrays**

Ocean Renewable Power Company (ORPC) is an alternate type of in stream tidal generation system, which uses unique cross-flow turbines that drive a permanent magnet generator on a single shaft. (Figure 4) These units can be stacked vertically and horizontally into much larger units. A 4x4 unit can produce about 763 kW in a 2.6m/sec tidal flow. The units use a permanent magnet generator and do not require a gearbox. Also, they turn in the same direction regardless of incoming or outgoing tide.

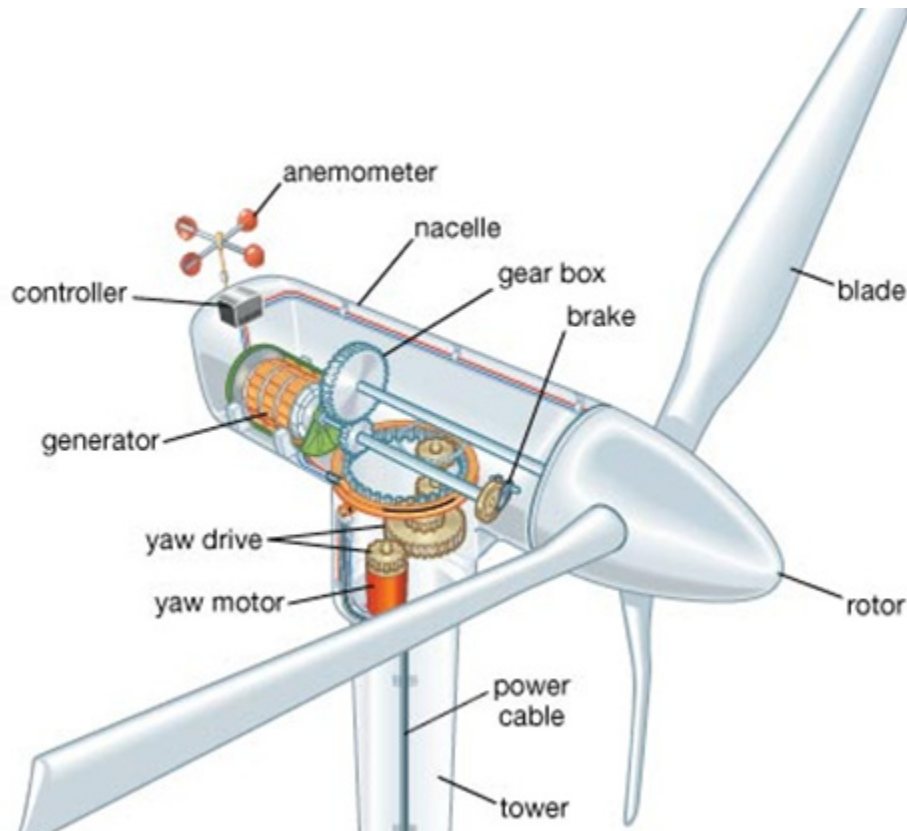


**Figure 4. ORPC Cross-Flow Tidal Generator**

## **1.2 Wind Energy**

Wind turbines have been used to generate electricity since the late 19<sup>th</sup> century, although the modern wind power industry did not begin until about 1979 when several European countries began commercially producing small wind turbines. Worldwide, wind power now has the capacity to generate 430 TWh annually, which is about 2.5% of worldwide electricity usage (Reference 3-4). In terms of potential wind generating power, as stated by DOE, offshore wind energy could potentially supply 4,000 TWh/yr in the US alone, and onshore wind energy could potentially supply an additional 37,000 TWh/yr (Reference 5). This total potential US wind energy is about ten times more than the entire 2010 US electricity demand of about 4,000 Twh per year (Reference 6), and wind energy costs are significantly lower than using natural gas, solar power, or coal with carbon sequestration (Reference 7).

The operating theory behind most present wind turbines is shown in Figure 5. Three blades are used to harness the wind and transfer their slow revolving torque to a gearbox. The gearbox increases the RPM to about 1800 RPM, and the attached alternator then generates electricity. At high wind speeds, total efficiency is close to about 80% of theoretical values, but this drops greatly at slower wind speeds. Not only does the total available power drop off according to the cube of velocity, but the relative efficiency of the gearbox and alternator greatly decrease with wind speed.



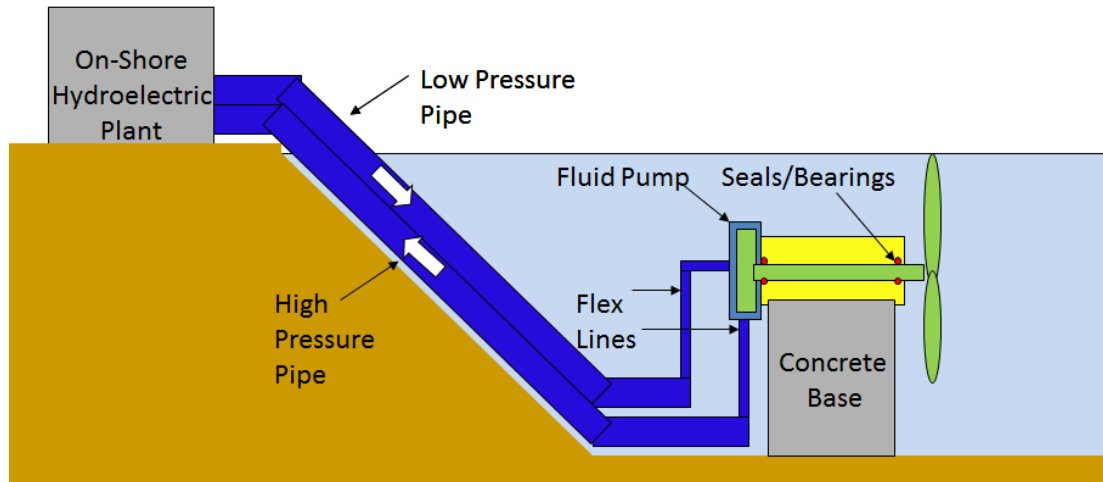
**Figure 5. Typical Wind Turbine Components**

The gearboxes are the primary failure mode for wind turbines, and servicing the generator or gearbox at the top of the wind mast is the primary maintenance cost related to conventional wind turbines. There are three European companies (Chap Drive/Norway, Artemis/Scotland, and Voith Turbo WinDrive/Germany) that have replaced the top-mounted wind turbine gears and generator with a top-mount hydraulic pump. The hydraulic pump then pumps oil to a hydraulic generator at the bottom of the mast. The two big advantages to this type of design are that the gearbox is completely removed, and maintenance on the ground level generator is greatly facilitated.

Delft University in the Netherlands has taken hydraulic wind power generation one-step further for offshore wind power generation. They use a hydraulic oil loop on the mast to power a seawater pump that pumps high-pressure seawater to a generator on a remote platform (Figure 6). Electricity from hydroelectric generators is then transferred to shore by means of a buried cable (Reference 8).

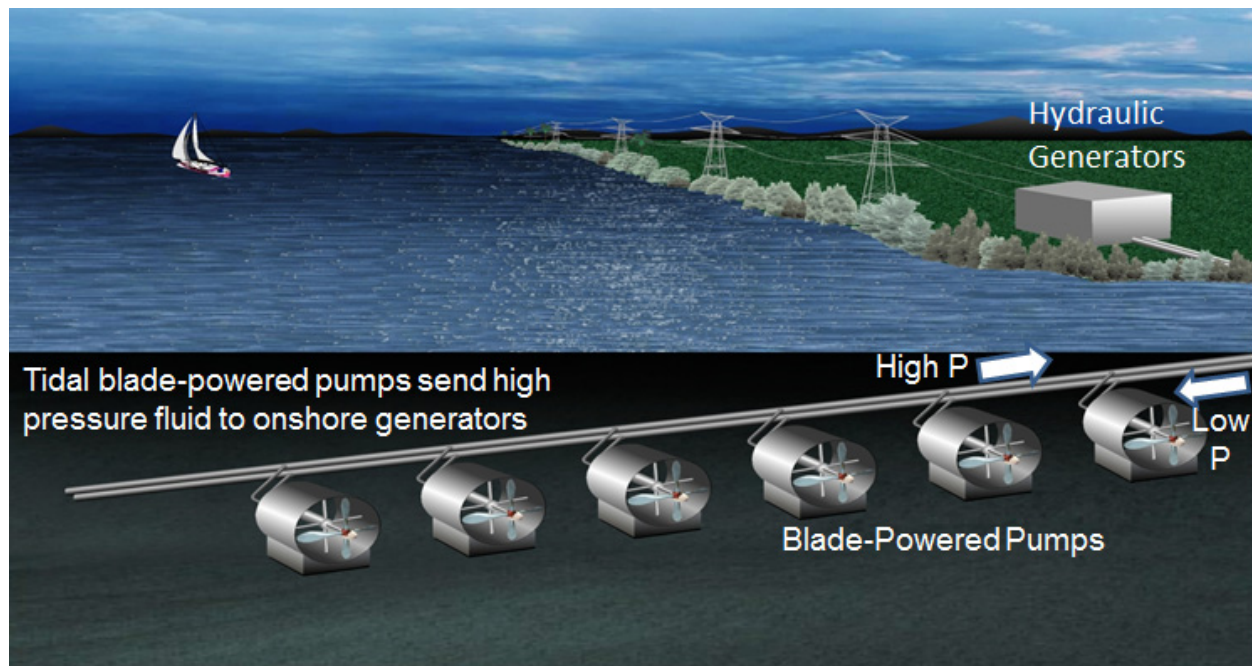


efficient, on-shore hydroelectric power plant. This all-mechanical design is less expensive (Reference 9), more efficient, and eliminates all gears and all submerged electrical component corrosion. A 500-m long, 0.35-m inside diameter pipe at 200 bar (2900 psi) can efficiently deliver 15 MW of hydraulic power to shore.



**Figure 7. JPL/Caltech Hydraulic Tidal Concept**

A series of HET tidal blade units can be combined such that the units are attached to a common high pressure line that delivers high pressure fluid to an onshore power plant (Figure 8). A separate line can then deliver low pressure fluid back to each of the HET tidal blade units.

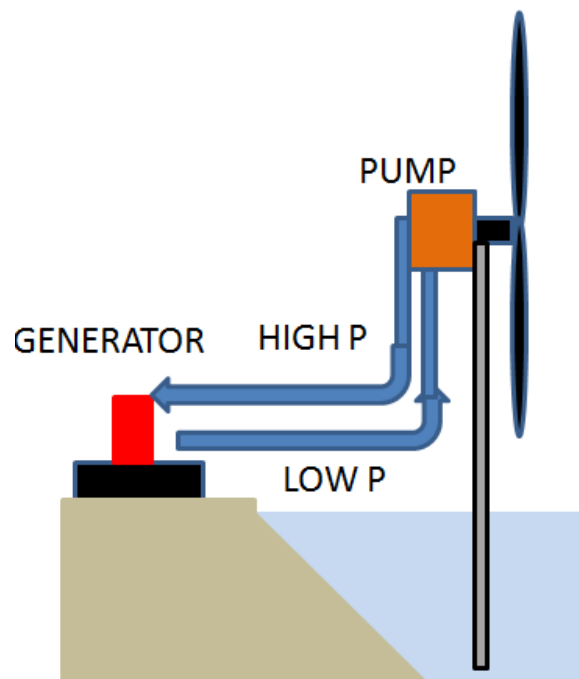


**Figure 8. JPL/Caltech Hydraulic Energy Transfer Schematic**

The DOE is presently funding JPL and Sunlight Photonics (FY'11-'12) to test a 15 kW hydraulic energy transfer tidal energy system that pumps environmentally friendly, biodegradable fluid to a remote, hydroelectric generator. A design is also being made for a 15 MW system in Maine's Western Passage tidal area. Both systems eliminate all gears and submerged electronics, thus greatly improving tidal energy reliability. Caltech has recently been granted patent rights to use this closed cycle hydraulic transfer design for tides, ocean currents, ocean waves, offshore wind, and onshore wind (Reference 10). Both the experimental 15 KW system and the analytical design of the 15 MW systems will be described later in the paper.

## **2.2 Wind Hydraulic Energy Transfer**

JPL/Caltech has taken the wind hydraulic energy transfer systems described in Section 1.2 an additional step further. For offshore and onshore wind energy, the top-mounted pump is used to pump environmentally friendly hydraulic fluid from a series of wind blades directly to a series of generators that are remotely located. For the case of offshore wind, the generators can be located onshore or on a platform offshore (Figure 9).



**Figure 9. JPL/Caltech Offshore Wind with Hydraulic Energy Transfer**

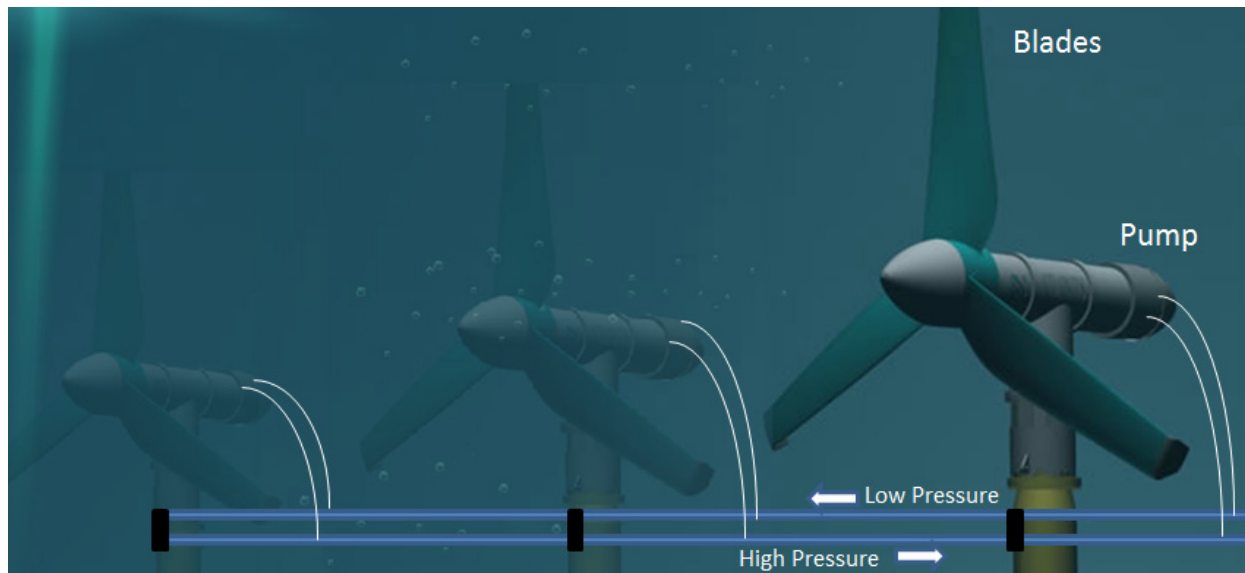
For onshore wind generation, the pumps can connect to a common high-pressure line that goes to a series of remotely located generators. The returning low pressure fluid



major energy loss and maintenance problem. The MB2400 has a maximum allowable speed of 24 RPM and maximum power output of about 1.41 MW. There are a variety of onshore hydraulic motors and generators that can generate 1800 RPM electricity at a combined efficiency of about 90%.

A high-pressure hydraulic line and low pressure hydraulic line are attached to the vertical strut of each blade unit. Flexible high-pressure outlet lines and low-pressure inlet lines connect the Hagglund pumps to the permanent lines (Figure 11). The preferred hydraulic fluid is HEPG (polyethylene glycol), which is a non-toxic, environmentally friendly, biodegradable oil that is used as a food additive and is fully miscible with water. Polyethylene glycol has been shown to have long term, low toxicity to aquatic organisms with amounts below about 1% (Reference 11).

The average ID of the high pressure (300 psi or 207 bar) stainless steel pipe is 35 cm and the average ID of the low pressure (150 psi or 10.3 bar) reinforced fiberglass pipe is 40cm. The pipe diameters would be somewhat larger near shore and smaller further away from shore to account for the varying amount of HEPG flow that is carried in the pipes. Total pressure drop in the high-pressure pipe is eight bars, and it is two bars in the low-pressure pipe, or 5% loss total of the entire flow for the 500-m x 2 roundtrip length.



**Figure 11. Atlantis Resource 18-m Blades with Hydraulic Energy Transfer**

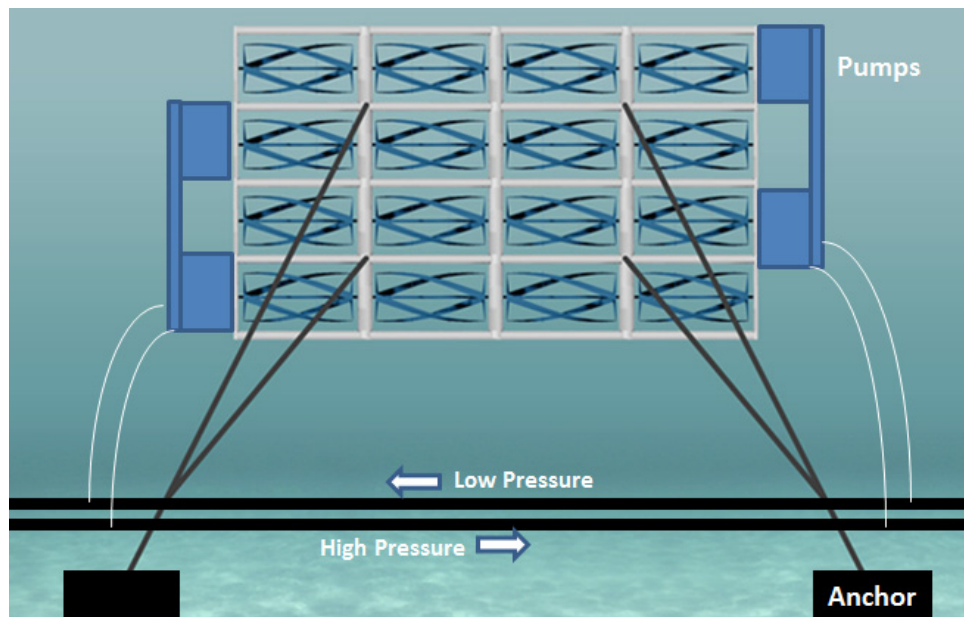
Preliminary cost for the subsea components, including installation is about 3.15 cents per watt, and preliminary cost for the onshore generating components, including power conditioning and grid connection, is about 60 cents per watt. Thus, total preliminary cost for power generation is about 3.75 cents per watt.

### **3.2 Hydraulic Tidal System with ORPC Cross-Flow Blades**

An alternative to the use of Atlantis' 18-m tidal blade design is the use of the Ocean Renewable Power Company (ORPC) cross-flow turbines (Figure 4). The ORPC design has the advantage that the turbine rotates in one direction only, regardless of current flow direction, and the generator does not require a gearbox.

In lieu of the ORPC submerged generators, it appears possible to install submerged pumps, similar to those mentioned above for the Atlantis 18-m blades. For this design, we would still use a 4x4 matrix for each tidal generation unit, but we would replace the four submerged generators with four gearless, Hagglund CM 280 pumps. In all, we would have six, 4x4 units, one of which is shown in Figure 12, to produce a total of 4 MW peak power. Total hydraulic conversion cost for the ORPC system has been estimated to be about 50 cents per watt, less the cost of the expensive submerged gearless generators, which would be eliminated.

For the ORPC hydraulic design, the high-pressure stainless steel pipes would average 20 cm ID, and the low-pressure reinforced fiberglass pipes would average 25 cm ID, to again give a total system pressure drop loss of 5%. The total amount of non-toxic, environmentally friendly, biodegradable polyethylene glycol would be about 10,000 gallons. Since it is fully miscible with water, if the entire quantity of glycol would leak in a single tidal flow, total mixed content of glycol with seawater would be about 30 parts per billion, assuming complete mixing.



**Figure 12. ORPC Cross flow Blades with Hydraulic Energy Transfer**

### **3.3 Hydraulic Transfer for Onshore and Offshore Wind**

For onshore and offshore wind, a small 15-MW system has been sized, although much larger power systems can be scaled up. We have selected 1.0-MW blade sets that are 60-m diameter and that rotate at 20 RPM for a maximum velocity wind of 12 m/sec (27 MPH). Each set of blades is connected to a Bosch-Rexroth/Hagglund radial piston pump #MB2400-1950.

For this particular example, we assume the generators are located 500-m away from the wind-pump units, and thus, the 15 MW fluid transfer system is identical to that of the Atlantis Resource hydraulic tidal system described in section 3.1. The average ID of the high pressure (3000 psi or 207 bar) stainless steel pipe is 35 cm and the average ID of the low pressure (150 psi or 10.3 bar) RFP pipe is 40 cm. total pressure drop is again 5% loss total of the entire flow for the 500-m x 2 roundtrip length. Distances longer than 500-m would require larger diameters in order to maintain the same 5% total pressure drop loss.

The total efficiency of the wind circuit is as follows for full rated wind speed:

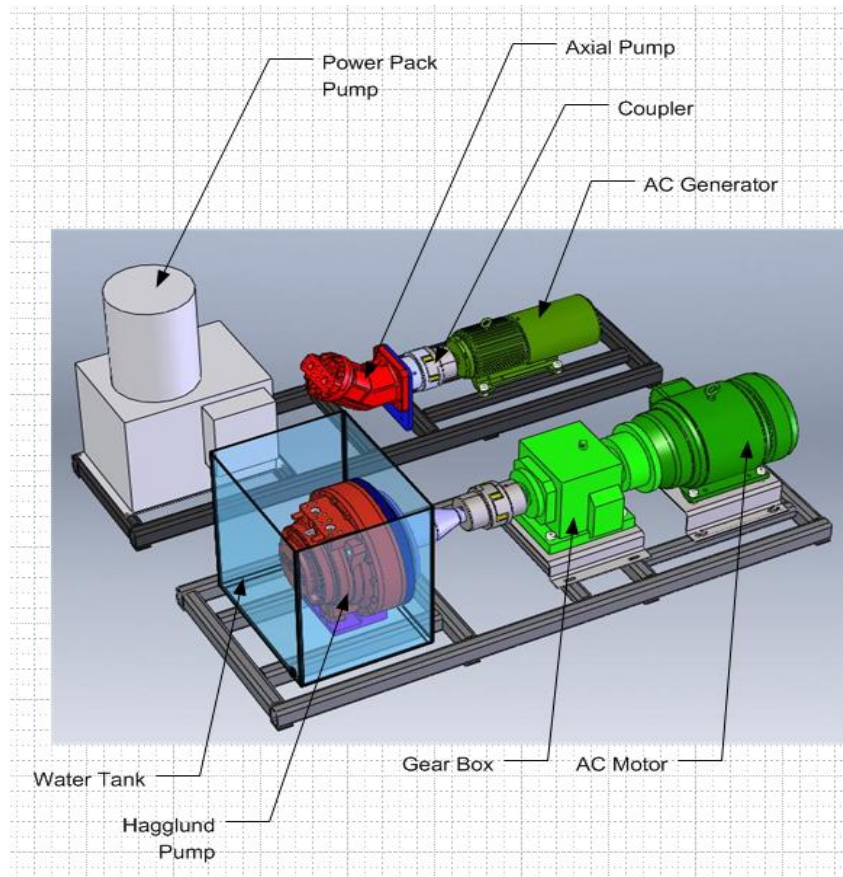
$$\begin{aligned}\text{Total Wind Efficiency} &= \text{Pump Effic} * \text{Pressure Effic} * \text{Hydraulic Motor Effic} * \text{Generator Effic} \\ &\sim 0.94 * 0.95 * 0.95 * 0.95 \\ &\sim 0.806\end{aligned}$$

At 1/3 full rated wind speed, pump efficiency increases to about 0.96 and the pressure drop efficiency increases to at least 0.99, while the hydraulic motor and generator efficiency stay at 0.95 by means of shutting off generators. Thus, total efficiency **increases** to about 0.858. This is a large improvement over other wind turbine systems, which suffer significantly **lower** efficiency at low wind speeds. Conventional wind turbine combined gear/electronic efficiencies (Reference 12), excluding power conditioning, vary from about 0.89 (full rated wind velocity), to about 0.5 at 1/2 rated velocity, and to zero (1/3 rated velocity).

### **4. Hydraulic Tidal Simulation Test Set up**

In addition to sizing tidal and wind hydraulic transfer systems, another facet of this DOE task is to demonstrate a proof-of-principle hydraulic energy transfer design. At the time of this writing, the equipment has been assembled at Rutgers University, but not yet fully integrated for testing. As shown in Figure 13, a 15 kW AC motor drives a gearbox to simulate the torque and RPM of a 3 m/sec tidal flow on 2-m diameter tidal blades. The gearbox is then connected to a Hagglund's pump, which drives an environmentally friendly fluid to a hydraulic generator. It should be noted that the gearbox is only used to

simulate the correct tidal blade torque and RPM, and would thus not be in an actual tidal or wind operating hydraulic transfer system.



**Figure 13. Hydraulic Energy Transfer Test Setup**

## **5. Summary and Conclusions**

The reliability, maintainability, and efficiency of wind energy and tidal energy systems can be significantly improved by using hydraulic energy transfer designs. In both instances, all failure-prone gears are eliminated, and the electronics are moved to a convenient, more easily maintained, hydraulic power generating station. For tidal energy, all submerged electronics and gears are replaced by off-the-shelf, radial piston pumps, which pump environmentally friendly, water-miscible polyethylene glycol (HEPG) to on-shore hydraulic generators. For wind energy, the complex, top-mounted gears and generators are replaced by off-the-shelf, gearless, radial piston pumps, which pump the same HEPG fluid to a central, ground-located series of hydraulic generators, which are much more easily maintained.

By means of closing off some of the hydraulic generators during slow tidal or wind conditions, it is possible to maintain a nearly constant generator RPM with a high efficiency power output, which requires very little power conditioning. Total wind or tidal

energy fractional efficiency actually *increases* from about 0.81 to about 0.86 when rated velocities decrease by 1/3. Similar gearless hydraulic energy transfer designs can be used to harness tidal energy, ocean current energy, river current energy, offshore wind energy, onshore wind energy, and ocean wave energy (Reference 10)

## **6. Acknowledgements**

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